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DESIGN OF A LOW-COST SERIES ELASTIC ACTUATOR FOR APPLICATION IN ROBOTIC MANIPULATORS

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Abstract. *The development of technologies in Human-Robot Interaction (HRI) field has increased with the concern to create robots that can perform dynamic tasks to collaborate with humans. One of these technologies is the Series Elastic Actuator (SEA), which offers advantages such as high quality of force/torque control, low impedance and shock tolerance. Flexibility is added to the robot by an elastic element (usually a spring) between each motor and its load. This paper presents the design of a modular and low cost eSEA (elastomer-based Series Elastic Actuator) for applications in robotic manipulators. The proposed eSEA is composed of three parts: the rigid internal and external parts are made of aluminum, while between them there is an elastic element made of an elastomer. Two encoders attached to each rigid element are then used to evaluate in real time the joint angles and the deformation of the elastic element. The eSEA is 3D modeled in software Solidworks and motion simulations are implemented in the ANSYS software. Experimental tests are performed with two different elastomers: the first with a very low hardness about 9-10 Shore A, while the second with about 55 Shore A. A test bench is created to obtain the torque x angular displacement profile of the developed eSEA, identifying elastic constants and sensor resolution. In the experiments, to generate known torques, test weights are positioned on a lever arm attached to the external part of the eSEA and to one of the encoders. These torques are compared to the torques measured by the controller board. The internal part of the SEA is attached to the motor axis, which is then connected to the second encoder. The calibrated eSEAs are mounted on especially developed planar robotic arms based on a 4-bar linkage, where their ability to estimate joint torques is used to improve the force and displacement control characteristics of the robot.*

Keywords: *Series Elastic Actuator, Human-Robot Interaction, Flexible Joint*

1. INTRODUCTION

New ways of working with the cooperation between humans and robots have been creating COBOTS (collaborative robots), which involve robots to have a certain flexibility in order to adapt to the environment and the partnering activities. In certain cases, such as precision work, this rigidity is necessary, but in cases where there is contact with humans, the manipulator must be flexible. If these two variables are needed in the activity (precision and contact), a balance must be made for the best possible control. The Series Elastic Actuator (SEA) is a type of actuator that has an elastic element between the motor and the link, and that allows the robot to better interact with humans. Besides the SEA that has a fixed stiffness, there is also a class of actuators with variable stiffness (Variable Stiffness Actuator - VSA).

Some advantages of the SEA are listed in Robinson *et al.* (1999) as improved force output, shock tolerance, low impedance and low cost. SEA has proven to be an alternative with high potential and low-cost add not only in industrial robots but also in research robots and has been widely used in mechatronics applications, especially in exoskeletons and humanoids. De Luca and Book (2016) state that this mechanical flexibility ensures a decoupling of the actuator with the link, reducing the kinetic energy involved in unknown collisions. Also the motor and perturbation torques become physically colocalized, an important feature for vibration rejection.

Increasing the spring constant increases both the natural frequency of the system and the bandwidth of the torque control. However, a stiffer spring reduces the spring deflection and thus the resolution of the torque sensor (Robinson *et al.*, 1999). Another drawback in this actuator is the inherent hysteresis of the material that can cause relevant inaccuracies in the measurements. Nevertheless, this application demonstrates to have a great potential in quadruped, biped, dual-arm robots, and wearable robots (Lee *et al.*, 2017).

Recent works (Haninger *et al.*, 2020, DeBoon *et al.*, 2020, Mavinkurve *et al.*, 2021) deal with the control of SEA in order to increase its efficiency regarding disturbances and nonlinearities. In researches of (Shi *et al.*, 2020, Lopes and Meggiolaro, 2020, Roozing *et al.*, 2021) perform case studies where effects of SEA actuation can be verified. Generally works with SEA use only one spring with linear actuation to study control techniques, however, a lack of damping can lead to undesired oscillatory motion and discomfort for the user when it uses for rehabilitation robotics. Then, a potential solution is to utilize an elastomer-based element in place of a traditional spring (Jarret and McDaid, 2019). A number of recent researches based on the geometry and/or the material, which is made the elastic element, as shown in Figure 1.

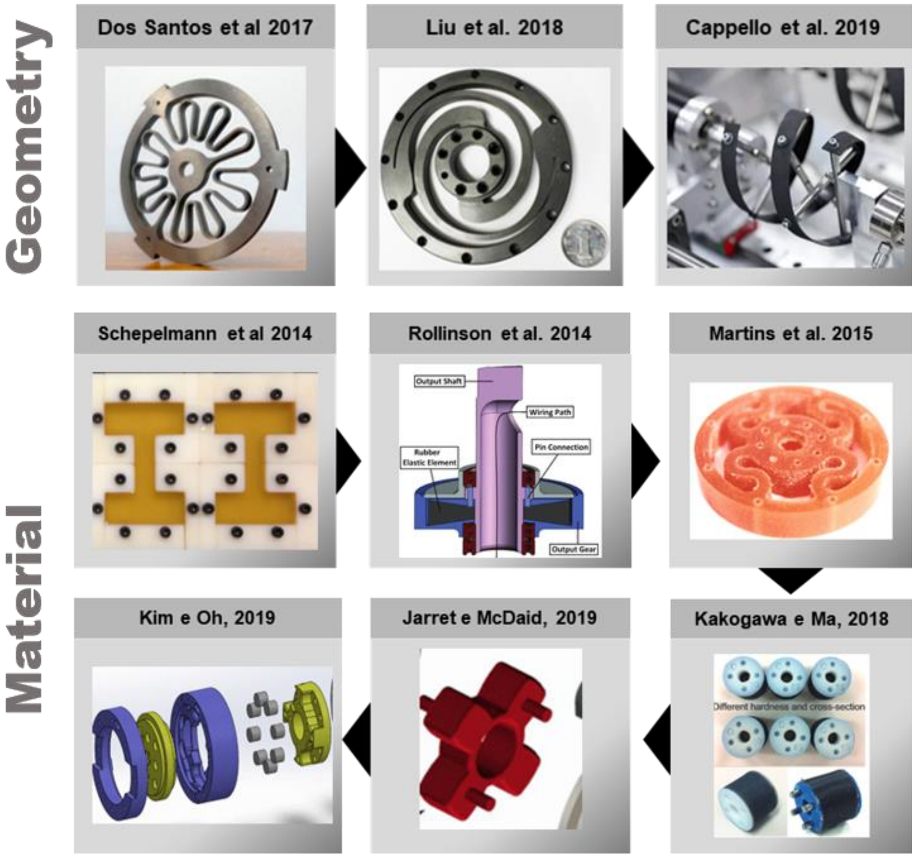

Figure 1. Examples of elastic element of SEA based on geometry and/or the material.

In the rehabilitation research by Dos Santos *et al*. (2017) it has a customized element used in people respecting the required maximum torque and gives the possibility to regulate the impedance in walking. In Liu *et al*. (2018) they studied a custom torsional spring to reduce the volume in the joints of the manipulator and evaluated the vibration in the system by means of RRC control. In addition, they made the system more robust by adding disturbance observers (DOB) for both the motor and the link assembly. In this way, it was possible to compensate for external disturbances and system uncertainties. Cappello *et al*. (2019) introduced the concept of multivariable SEA, where the motor is connected to an elastic element that has multiple equilibrium configurations. Thus, it was possible to increase the desired efficiency and release more energy.

As for material-based SEA, generally elastomers are responsible for transmitting the torque from the motor to the link. Schepelmann *et al*. (2014) present a passive nonlinear spring concept that uses rotating cams to lengthen these springs and thus create flexibility in the system. With this system, it was possible to recreate user-defined nonlinear torque profiles. In the work by Rollinson *et al*. (2014) they addressed a modular system with SEA that was daisy-chained together in the shape of a snake (Snake Robot). Each module has Ethernet connection, IMU sensor and ARM controller. The robot was able to control position, speeds and torques but they discussed some improvements since the rubber material properties are sensitive to temperature changes in the environment. Martins *et al.* (2015) present a different type of SEA that relies on geometry to create the spring effect but also makes use of the material, in this case they designed a polyurethane disk using finite elements. The mechanical system is easy to manufacture and the electronics was designed for the Arduino platform. Also highlighted are studies by Kakogawa and Ma (2018) that present an inspection robot with many links that uses the rubber-spring SEA. This configuration was purposeful to make the size of the robot smaller and increase the rigidity of the joint. In Jarret and McDaid (2019) they present the use of elastomer-based elements in place of springs as a potential solution. The model called eSEA (Elastomer-based SEA) was tested on an exoskeleton and presents an elasticity study as well as hysteresis evaluation. Finally, in Kim and Oh (2019) presented an eSEA with a set of circular elastomers spaced equally and that upon receiving torque from the motor, one set of elastomers receives that torque while the others move away from the base. They proposed a hysteresis model and compensation method to estimate the torques and they came up with a 10% better hysteresis model compared to Hooke's Law.

This work takes the SEA based on material stiffness and proposes an adaptable and low-cost eSEA to use in robotic manipulators. To generate the movement, were designed two parts (one internal and other external) which hold the elastic elements between them. After selecting the appropriate elastic element for the manipulator, were performed experimental tests to validate the proposed eSEA.

2. DESIGN OF THE SERIES ELASTIC JOINT

2.1 Requeriments

The work proposes to design and develop a lightweight, modular and low-cost eSEA for use in robotic manipulators that have safe interaction with humans. More precisely in a dual-arm robot developed to work with coordination tasks. Therefore, was selected a rubber to be the elastic element of the assembly.

Figure 2 shows the eSEA designed in this work. Essentially, the motor shaft rotates the inner part of the eSEA while the outer part rotates due to the elasticity of the rubber positioned between these two parts (inner and outer parts). The shaft of the inner part has the diameter of the motor shaft (8mm) and the outer part has holes connected to the encoder and link by screws. The eSEA design was elaborated to ensure a symmetrical response in both direction and to have no sliding. Using these constraints, were studied several combinations for the eSEA.

The shape designed in SolidWorks and simulated in ANSYS the minimum angular displacement that the eSEA could perform and the encoder could measure. The minimum displacement that the encoder can measure is 0.043° and was achieved a minimum eSEA displacement of 0.26° by the simulations.

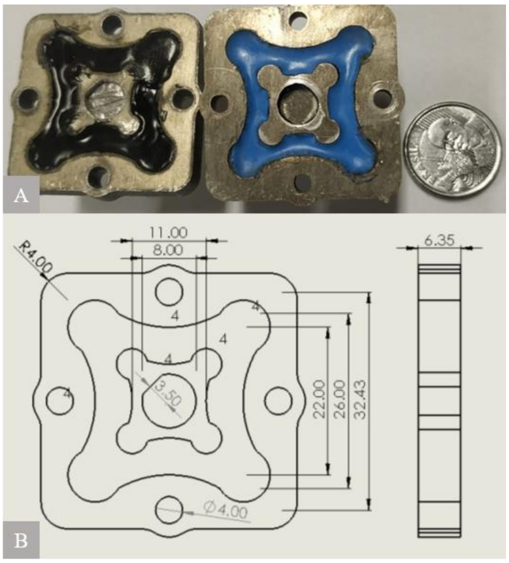

Figure 2. Example of eSEA proposed. A) The two elements with different stiffness. B) Project dimensions.

2.2 Manufacture

The manufacture of the mechanical parts was performed with waterjet cutting on aluminum 7075-T6 parts to produce the inner and outer parts of eSEA with thickness of 6,35mm. For the inner element, were selected rubbers with different stiffness. The blue rubber has stiffness about 9-10 Shore A and is widely used in molding. For its production, is used a catalyst in the proportion of 3% over the weight of the rubber to be used (100g of rubber for 3g of catalyst for example). The black rubber has stiffness about 55 Shore A and is widely used in tires. The catalyst proportion of this harder rubber is 5%. Figure 3 compares the hardness of the elastic element with other known materials.

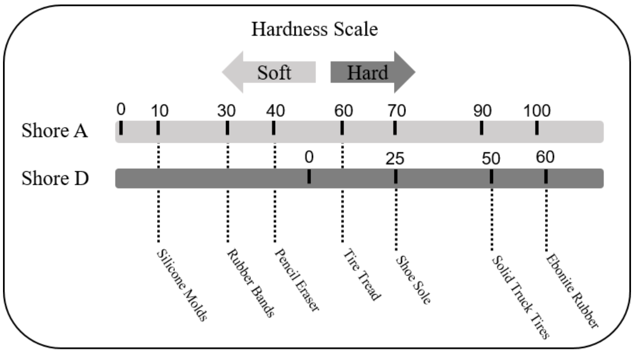

Figure 3. Hardness Scale to compare the eSEA produced. Adapted from ElcometerUSA (2021).

It was necessary to create a custom-build molding base for depositing the rubber onto the aluminum parts so that the positioning parts correctly. This prevents the inner part from rotating when depositing the rubber. Two base materials are mixed and injected into this custom-build molding base with the inner and outer parts. Finally, the curing process takes a minimum of 24 hours for the elastic element to stick to the aluminum parts and present the necessary stiffness. For understanding, this work refer to the blue rubber and the black rubber as eSEA 10A and eSEA 55A respectively. The Table 1 presents characteristics of these eSEA.

Table 1. Properties of eSEA 10A and eSEA 55A.

eSEA	**Mass (g)**	**Thickness (mm)**	**Width (mm)**	**Catalyst (%)**
10A	24	6,35	40.43	3
55A	26	6,35	40.43	5

2.3 Electronics

The assembly (see Figure 4a and 4b) has a dual shaft D5065/270KV brushless DC motor that reaches a maximum torque of 1.99 Nm, two CUI AMT102 incremental encoders with a resolution of 8192 CPR, and a range of 7500 RPM. One encoder is responsible for the angular position of the motor and the other for the angular position of the link (the external part of the eSEA). An ODrive Robotics board controls the assembly and the algorithms are in Python language. Finally, the link is between the elastic element and the incremental encoder (see Figure 4c).

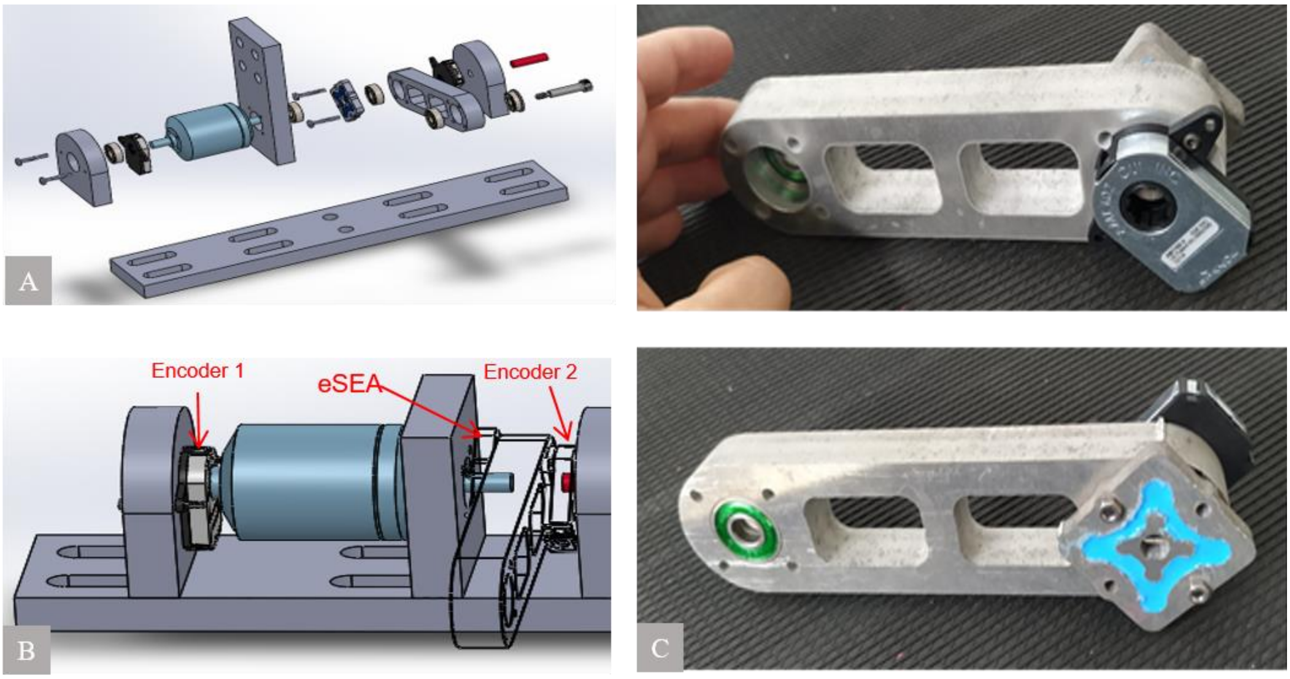

Figure 4. Assembly of the system with eSEA. A) Exploded view. B) Position of eSEA, encoders and motor. C) Assembly of eSEA, encoder and link.

3. EXPERIMENTAL SETUP

3.1 Test Rig

The experiments conducted a static test of the system. While holding the motor in a determined position, known weights are applied with the use of negligible mass wire. These weights applied to a lever with a specific size allow calculating the external torque caused on the motor. Considering a linear torsional stiffness described by Hooke's law given by:

$$\boldsymbol{\tau} = -k.\boldsymbol{\Delta\theta}, \tag{1}$$

Where $\boldsymbol{\tau}$ is the torque spring, k is the elastic constant of torsional spring and $\boldsymbol{\Delta\theta} = \boldsymbol{\theta} - \boldsymbol{q}$ is the elongation of eSEA.

Figure 5 shows the experimental apparatus developed to calculate the elastic constant. The lever is 130 mm long and 4 mm thick and printed by additive manufacturing using PLA material. This lever has three holes of 45 mm apart and is positioned between the eSEA and the encoder.

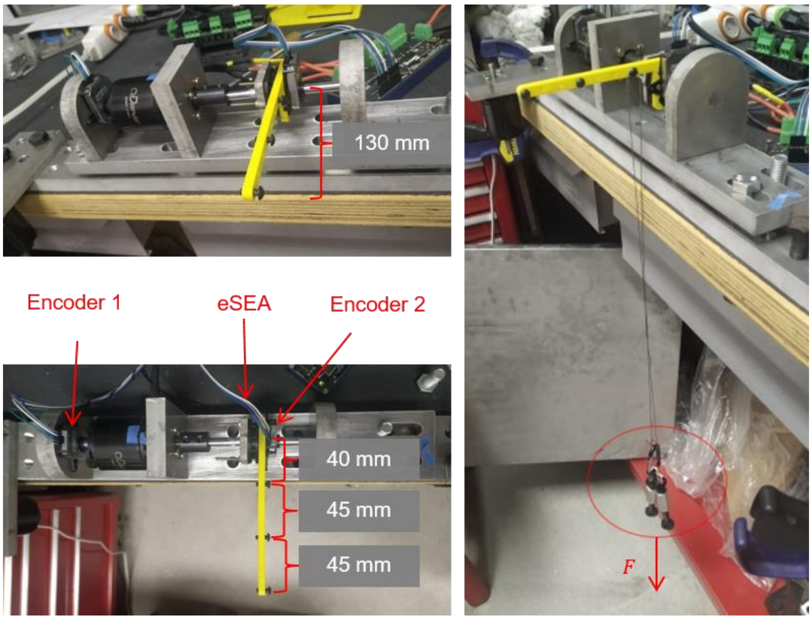

Figure 5. Test rig for calculate the elastic constant of eSEA.

Therefore, the motor rotates the inner part of the eSEA causing angular displacement θ whereas, the lever and the encoder rotate with the outer part of the eSEA due to the elastic element causing angular displacement q. Knowing the distance applied to the weight force, it is possible to calculate the torque using Eq. (2) and thus generate a Torque x Elongation plot to estimate the value of k.

$$\boldsymbol{\tau} = d \; x \; \boldsymbol{F}, \tag{2}$$

3.2 Validation

The validation of the elastic constant uses a strain gage sensor to measure the force of the eSEA. In this way is selected a desired position θ_{des} for the motor and then measures the elongation (relative angular displacement between encoder 1 and encoder 2) and the force felt by the strain gage. Figure 6 represents the experimental device for these tests.

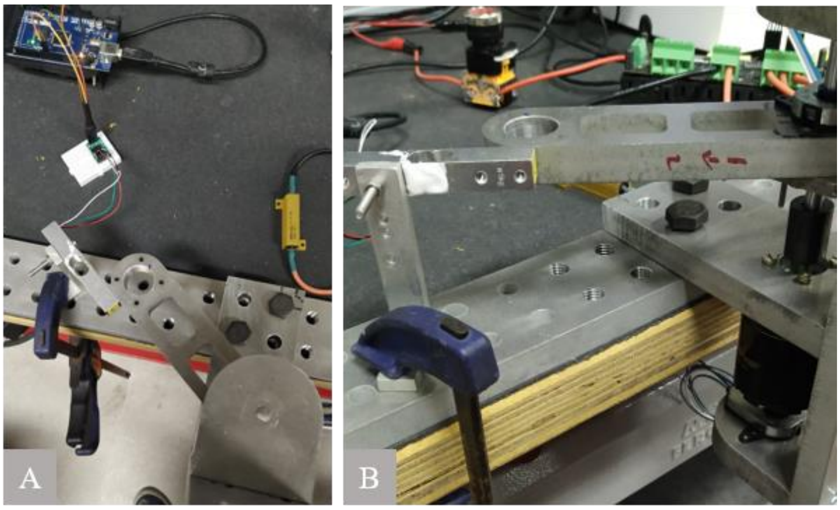

Figure 6. Test rig for validation of elastic constant of eSEA. A) Top view of the experimental device. B) Front view of the experimental device

4. RESULTS

The data collection performed averaged 50 samples for each weight and Table 2 presents the results obtained and illustrated in Figure 7 (eSEA 10A) and Figure 8 (eSEA 55A).

Table 2. Experimental results for static tests of eSEA.

Measures	Mass (Kg)	Force (N)	Torque (Nm)	Elongation 10A (rad)	Elongation 55A (rad)
Loading	0	0	0	0	0
	0,1875	1,839375	0,156346875	0,091905583	0,014261228
	0,2795	2,741895	0,233061075	0,137158016	0,023843095
	0,3707	3,636567	0,309108195	0,174369034	0,035341479
	0,4619	4,531239	0,385155315	0,187383903	0,042639872
	0,499	4,89519	0,41609115	0,197750257	0,044940843
Unloading	0,499	4,89519	0,41609115	0,197750257	0,044940843
	0,4619	4,531239	0,385155315	0,190080353	0,043406863
	0,3707	3,636567	0,309108195	0,177413027	0,040710412
	0,2795	2,741895	0,233061075	0,145199431	0,032668997
	0,1875	1,839375	0,156346875	0,10477664	0,024115376
	0	0	0	0	0

From the Torque x Elongation plots, it is possible to estimate the values of $k_{10A}$and $k_{55A}$for the elastic elements using the linear regression method. Given a linear equation $y = k.x + a$, the value obtained for $k_{10A} = 1.9824$ Nm/rad (or 0.0346 Nm/deg) and for $k_{55A} = 8.549$ Nm/rad (or 0.1492 Nm/deg). It is assumed that the residual values of the linear equation (a) were measurement errors.

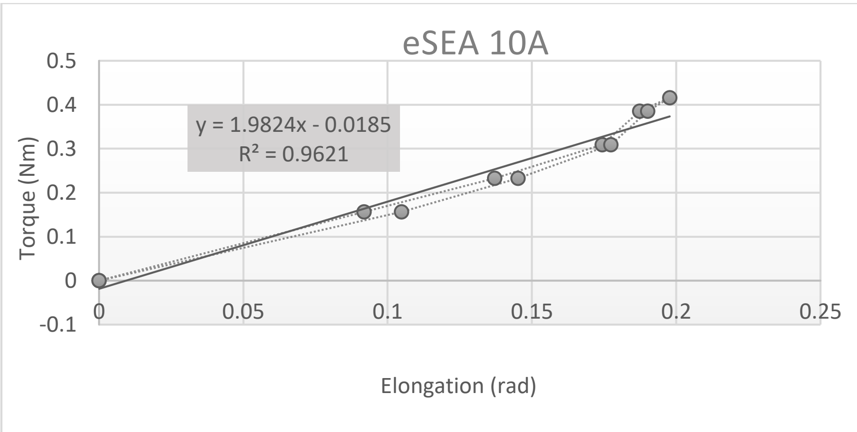

Figure 7. Static test of eSEA 10A.

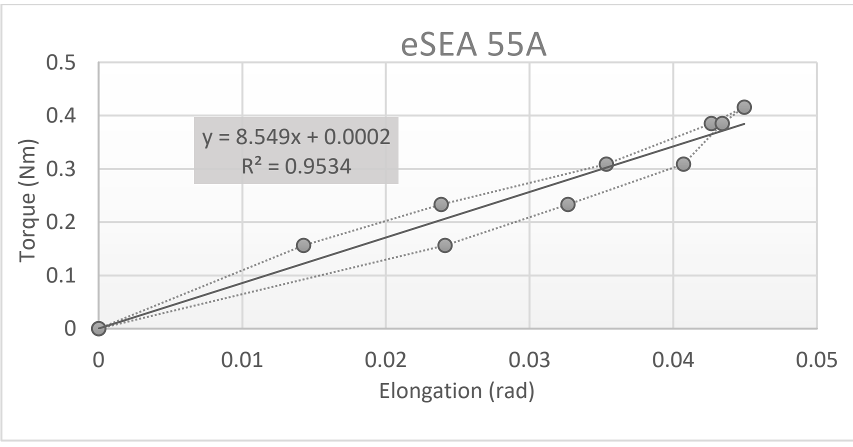

Figure 8. Static test of eSEA 55A.

Table 3 shows the values from the validation tests of the eSEA produced. For each sample, the load cell measures the torque performed, and the eSEA estimates these torque values. Figure 9 compares these values and shows the ability of the designed eSEA to estimate torque.

Table 3. Validation of eSEA proposed.

Samples	Estimated eSEA 10A (Nm)	Measured eSEA 10A (Nm)	Estimated eSEA 55A (Nm)	Measured eSEA 55A (Nm)
1	0.0115	0.0165	0.0850	0.0777
2	0.0289	0.0318	0.1633	0.1566
3	0.0485	0.0483	0.2456	0.2260
4	0.0673	0.0706	0.3339	0.2990
5	0.0838	0.0871	0.4186	0.3849
6	0.1044	0.1036	0.4934	0.4650
7	0.1222	0.1201	0.5702	0.5521
8	0.1404	0.1354	0.6533	0.6475
9	0.1591	0.1495	0.7401	0.7511
10	0.1785	0.1589	0.8212	0.8629

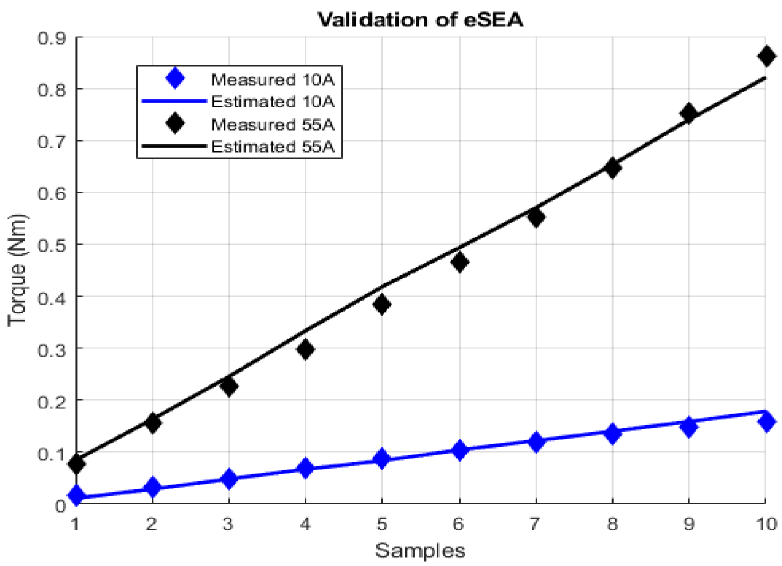

Figure 9. Validation of eSEA 10A and eSEA 55A.

Figure 9 shows that despite considering a linear elastic constant for the prototype, eSEA 10A can estimate the motor torque better than eSEA 55A. This can also be noted in the Torque x Elongation curves (Figure 7 and Figure 8) showing a larger hysteresis in the harder elastic element (eSEA 55A). The values of the constants are higher than the value used in previous work (Lopes and Meggiolaro, 2020), which allows us to evaluate that these constants can be used in the manipulators concerned.

Kakogawa and Ma (2020) present SEA with torsional springs stiffer than this work ($k = 0.431$ Nm/deg) which are made of polyurethane but with value close to eSEA 55A. Likewise, eSEA 10A obtained value close to the work of Martins *et al*. (2015) that also uses polyurethane but takes advantage of the geometry to generate angular displacement.

5. CONCLUSIONS AND PERSPECTIVES

This paper designed an elastic element with rubber to use as an eSEA (Elastomer-based Series Elastic Actuator) to estimate torques in robotic manipulators. The proposal created a low-cost and simple to manufacture SEA. The eSEA proposed is intentionally designed to be modular. Depending on specific torque requirements, it is easy to change the elastic element and thus able to be used in different tasks. This work also covers the construction and operation of an experimental device to calculate the elastic constant. We validated the calculated constants on a test bench and compared them with existing works in the literature.

Since the presence of hysteresis may cause errors in torque estimates especially at high speeds, it needs a more accurate model for the elements. In addition, we consider studies of Mullins' effects and relaxation in future work.

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